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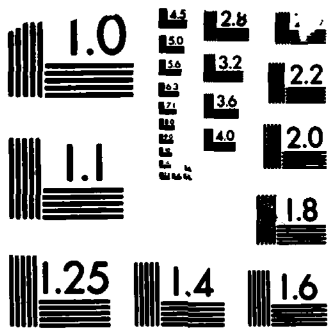

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FAST ELECTRICAL AND OPTICAL DIAGNOSTIC PRINCIPLES AND TECHNIQUES: A NATO ADVANCED STUDY INSTITUTE

M. FRANK ROSE
NAVAL SURFACE WEAPONS CENTER

21 November 1983

UNITED STATES OF AMERICA

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The institute was divided into the following major sections: (1) overview of applications and needs (2) voltage and current measurements, (3) data acquisition, (4) grounding and shielding, (5) fast photography, (6) refractive index measurements, (7) X-ray diagnostics, (8) spectroscopy, and (9) active optical techniques. The report examines these topics and provides tables comparing various nanosecond instrumentation techniques.

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FAST ELECTRICAL AND OPTICAL DIAGNOSTIC PRINCIPLES AND TECHNIQUES: A NATO ADVANCED STUDY INSTITUTE

Because many natural processes of practical interest are governed by fundamental phenomena which occur on the nanosecond time scale, there is growing interest in the techniques for obtaining, recording, and analyzing fast temporal data. These phenomena are important in areas such as breakdown and conduction processes in various media, electromagnetic radiation production and propagation, particle beam accelerators, pulsed power technology, inertial and magnetic confinement fusion, and electric discharge lasers.

These technologies, by their very nature, present a harsh, "noisy" environment in which instruments must function. Often, because of the time scale and the sheer magnitude of the parameters involved, there are difficulties with standards and calibration techniques. Therefore, the measurement and analysis of fast physical events require an understanding of the basic principles underlying the diagnostics, their limitations, and the practical techniques which must be used to obtain reliable and repeatable data.

A 2-week NATO Advanced Study Institute (ASI) on Fast Electrical and Optical Diagnostic Principles and Techniques was held at Castelvecchio Pascoli, Italy, from 10 through 24 July 1983. The ASI was organized by Mr. L. Luessen, Naval Surface Weapons Center, as the Administrative Director, and Professor J.E. Thompson, University of South Carolina, as the Technical Director. The institute was attended by 107 participants representing the US, West Germany, the UK, Switzerland, Norway, The Netherlands, Italy, and France. (See the appendix for a list of the participants.)

The institute was divided into the following major sections: (1) overview of applications and needs, (2) voltage and current measurements, (3) data acquisition, (4) grounding and shielding, (5) fast photography, (6) refractive index measurements, (7) X-ray diagnostics, (8) spectroscopy, and (9) active optical techniques. In addition, three sessions were made up of papers contributed by the participants. These papers were summaries of research programs employing high-speed diagnostics. Several companies also displayed and demonstrated high-speed diagnostic equipment and participated in the technical lectures. The ASI proceedings will be published by Martinus Nijhoff as part of their applied sciences series; the book should be available in the fall of 1984. These proceedings should provide a working textbook in instrumentation techniques applicable to a wide range of phenomena of major importance to Navy applications.

Overview of Applications and Needs

This section was headed by the author and Professor M. Kristiansen (Texas Tech University). In our lectures, we discussed the factors which are determining the needs for high-speed instrumentation. While many industrial processes and applications require high-speed diagnostics, practical considerations by the military have been a major driving force. Detonation physics, weapons effects (both conventional and nuclear), and inertial confinement fusion have accelerated the development of fast optical techniques capable of nanosecond time resolution. X-ray diagnostics were developed to allow imaging though obscuring media and to investigate the collapse of fuel pellets for fusion events.

Weapons effect simulation, inertial confinement fusion, and directed energy technology have stimulated the development of large electrical machines which produce terawatts of power on the microsecond time scale. The power flow must be controlled with great precision, and often the machines have size and weight constraints which necessitate their operation near the limits imposed by catastrophic failure. Often the power train is controlled by many switches which must function with nanosecond precision.

Since the terawatts of power imply megavolts and megaampere currents, there is a continuing need to develop new methods to measure these quantities, particularly new techniques which are nonintrusive. The factors limiting the performance of these machines are also of interest to the industrial community. The most prominent limitations are electrical breakdown and subsequent recovery, plasma chemistry, and electrical conductivity and its evolution as a function of time. These phenomena are of considerable interest in themselves and are the subject of major research efforts in industry and university laboratories.

From these studies, on the subnanosecond time scale, scientists are beginning to understand the intricate and complex processes which determine the late-time behavior of many devices. Picosecond time resolution allows essentially instantaneous measurement of plasma parameters such as ion/neutral densities, ion/neutral temperatures, electron distribution functions, excited state identification, electron density, and electron temperature. A strong basic understanding of these phenomena is critical to the development of devices which depend on them either to produce an effect or to provide a catastrophic limit.

In closing this section, Professor A. Hyder (Auburn University) proposed that the ASI participants collectively rank the various diagnostic techniques using factors such as time resolution, range of parameter to be measured, ease of use, cost, and accuracy. The resulting charts (Tables 1 through 8 in this report) represent a concise summary of the ASI and were much in demand by the participants. To my knowledge, this is the first time a comparison has been made of the various nanosecond instrumentation techniques. Because of the number of factors involved in a given experiment, the tables should be used only as a guide, but are useful in describing the relative merits of one technique over another.

Voltage and Current Measurements

This section of the ASI was headed by J. Chang (Diagnostics Division, Sandia National Laboratories). Generally included under this heading were measurements of voltage, current, electric and magnetic fields, and their time derivatives. The techniques discussed can be catagorized as conventional and passive/nonintrusive. The conventional techniques usually make measurements by physically intruding into the system with components such as resistors, capacitors, and connectors, and form possible breakdown paths. The passive/nonintrusive techniques use electro- or magneto-optic effects, such as the Kerr or Faraday effects, to produce a minimal perturbation in the system.

C. Baum (Air Force Weapons Laboratory) presented several theoretical lectures on the basics of electromagnetic measurements. These lectures began with field equations and finished with detailed mathematical descriptions of the factors which influence the design and limits of particular sensors' techniques for measuring $\bar{E}$, $\bar{H}$, I, V, and their time derivatives. The effects of source currents and conductivities were also included insofar as they introduce noise and ambiguity into the measurement.

The sensor output must always be connected to a recording device that is often remote from the sensor. Cabling, symmetry/topology, and other factors may affect the response. The importance of these factors in the overall instrumentation scheme was considered, and guidelines for factors such as cable dispersion and recording bandwidth were established.

The first experimental techniques to be described were the passive, isolating electro-optical and magneto-optical schemes. These techniques depend on the effect of electric and magnetic fields on the index of refraction of suitable media. The affected media are built into one arm of an interferometer, and a counting scheme is used to register the number of interference fringes produced when the field is applied.

There were five lectures in this area. The first, by R. Hebner (National Bureau of Standards), was introductory and tended to define in broad terms some of the advantages and disadvantages of optical techniques. Then specific applications, some capable of picosecond time resolution, were described by Professor G. Mourou (University of Rochester), M. Hugenschmidt (Deutsch-Franzosisches Forchungsinstitut), G. Chandler (Los Alamos National Laboratories), and Chang. The electro-optic techniques can be based on both the Kerr effect and the Pockels effect. The Kerr effect sensor is limited to liquid media which are suitably birefringent. The Pockels devices are solids and can be built into optical fibers which intrude passively into the system. Table 1 summarizes the electro-optical and magneto-optical techniques as presented by these lecturers.

Voltage and current can also be measured by intrusive techniques which involve resistive, capacitive, or inductive coupling to the system under measurement. In addition to the theoretical treatments of Baum, there were two major lectures dealing with these techniques.

The first, given by W. Pfeiffer (Technische Hochschule Darmstadt), was entitled "Ultrafast Electrical Voltage and Current Monitors." Pfeiffer indicated that special installations--paying great attention to factors such as geometry--could produce probes capable of time resolution in the 50- to 100-ps regime. These techniques are simple in principle, but short time resolution demands a great deal of experimental technique and must be custom-designed for the experiment under question.

In the second lecture, M. DiCapua (Physics International) presented a more general approach to the measurement of voltage and current by conventional techniques. Building upon earlier theoretical treatments, he discussed the design of diagnostic devices; he emphasized calibration, simplicity, mechanical design, and ease of use. He considered simple resistive dividers, current-viewing resistors/shunts, capacitive dividers, and inductive coupled devices such as current transformers and Rogowski coils. Auxiliary devices such as integrators and recorders were also discussed. Table 2 summarizes the techniques discussed by these lecturers as well as others from contributed papers.

Several other measurements can be used to deduce fields or potentials but are not as simple to categorize. For example, the measurement of free fields of the type associated with nuclear weapons effects must be done by antenna systems. These sensors measure the time dependence of the electrical displacement $\dot{\vec{D}}$ and the time dependence of the magnetic induction $\dot{\vec{B}}$. They were considered in some detail by C. Baum in his theoretical lectures. These devices are loop or stub antennas and require a primary standard for calibration.

A second class of unique voltage/current measurements is associated with nuclear effects and charged particle beams. A lecture by R. Leeper (Sandia National Laboratories), entitled "Nuclear and Particle Voltage and Current Measurements," introduced techniques for measuring currents and voltages (energy) by nuclear activation processes. The reactions used were ${}^{12}C(P,\gamma){}^{13}N$, $7Li(P,\gamma){}^{8}Be$ and $19_F(P,\alpha\gamma){}^{16}O$. By counting the gamma rays emitted when thin foils are bombarded by protons, one can use all these reactions to measure proton beam parameters. Resolution is limited by recorder and counting techniques. Table 3 lists a group of miscellaneous techniques for measuring current and voltage or parameters closely related.

Data Acquisition

Central to the measurement of electrical parameters are the techniques used in data acquisition and storage. This section was chaired by Hebner; there were nine lectures. The initial lecture by N. Camarcat (Commissariat a l'Energie Atomique) dealt with modeling of large electrical systems as a qualitative aid in understanding

measurements. The computer codes essentially predict voltage time, current time, and power flow in large terawatt-class electrical machines. To test the model, predicted parameters were compared with test results from machines such as OWL II and SIDONEX II, which are used in simulating the effects of nuclear weapons. The results were generally good and, while these codes were written for large machines, the same general approach is applicable over a wide range of parameters and produces a result similar to the nonlinear-circuit codes use in the US, such as NET II and SEPTRE.

It is often tempting to correct poor experimental practice by using software to adjust for factors such as noise and system response. N. Nahman (National Bureau of Standards, Boulder, CO) discussed in detail these techniques. He pointed out that one needs to have a pretty good idea of what the signal looks like in order to use, effectively and reliably, signal correlation and filtering techniques. This practice is becoming more and more popular as minicomputers are being interfaced to experimental assemblies. It is then an easy matter to have machine smoothing as an integral part of the data-handling package.

Mourou, Chandler, and DiCapua described various aspects of data transmission. The most interesting and useful would appear to be fiber-optic links which readily isolate, electrically, the measuring sensor from the recording device. With broadband optical isolators, analog-to-digital converters, and transient digitizers, it is easy to make reliable measurements in severe environments and transmit the data optically to remote recording facilities. This approach is becoming an accepted practice in much of pulsed power technology. Large-scale instrumentation schemes using fiber optics were described by Chang and DiCapua. The technical applications described involved multisensor systems used on the particle beam fusion accelerators (PBFA) at Sandia and the CAMAC data acquisition system at Physics International. The session closed with lectures on "Wave Form Recorder Applications" by S. Streiff (Nicolet Oscilloscope Division) and "Review of ADC Technologies for the Digitization of Fast Signals" by C. Flatau (Tektronix Europe B.V.). These techniques represent the state of the art and are discussed in the literature of the respective companies.

Grounding and Shielding

The group leader for this session was J. Wiesinger (Hochschule der Bundeswehr Munchen). He and Baum gave introductory lectures on the basic principles to be applied in grounding and shielding. Shielding can be implemented at the sensor/component level, the system level, and the enclosure level. All of these afford a certain degree of electrical isolation; in concert they can reduce total interference by almost an arbitrary amount--but not without penalties in, for example, the signal-to-noise ratio or sensitivity. For analysis, the overall scheme proposed above is divided into the source signal, the connectors, the cables, and the recording devices which are located in a shielded room. Each of these aspects was covered in some detail by W. Graf (Stanford Research Institute), whose paper was entitled "System Design and Practical Shielding and Grounding Techniques Based Upon Electromagnetic Topology," and by I.L. Hoeft (IBM Corporation) in his lectures entitled "Shielding of Cables and Cable Trays" and "Shielding of Enclosures." These lectures developed, within the framework of shielding practice, the concepts of skin depth, apertures, coupling, and transfer impedance, and applied them to cable connectors, various types of cables, and shielded enclosures. These applications were illustrated with measured results used to categorize shielding schemes. In general, one is able to achieve excellent electrical shielding and isolation in a laboratory environment, but such results are more difficult to

achieve in the field and on devices subjected to repeated maintenance.

Generally, heavy braid and solid pipe are the most cost-effective shields for cables. Using multiple layers of shielding is better than trying to eliminate problems with one "supershield," and joints and apertures are the most common problems to be dealt with at the enclosure level. The enclosure topology should be kept as simple as possible, and particular care must be exercised at joints. These should be plated and may or may not require finger stock or gasketing. At any rate, the transfer impedance, giving the amount of radiation transmitted as a function of that incident upon the system, is a good measure to adopt in describing shielding techniques. Penetrations must be rigidly controlled through triaxial connections or other suitable means.

The final lectures in this session dealt with the specific pulsed machines; both lectures were entitled "Grounding and Shielding of Pulsed Power Machines" and were given by Chandler and DiCapua. These discussions of grounding and shielding practice provided excellent examples of the application of the practical principles described in the previous lectures. The machines described were in the terawatt class, a particularly difficult region in which to provide adequate shielding. These systems tend to produce broadband "switch noise," enormous electrical fields, and sometimes hard X-rays. The effects of these "unwanted transients" must be eliminated if the diagnostic system is to produce repeatable, reliable results.

Up to this point, the ASI dealt with electrical/electromagnetic measurements as a diagnostic technique. Of equal importance are diagnostics which measure shape, size, state variables, and optical parameters. The second week of the ASI concentrated primarily on these techniques. It is convenient to divide them into optical/X-ray techniques--which measure geometry, topology, velocity, and parameters associated with changes in the index of refraction--and spectrographic techniques, which measure state functions of multicomponent systems. Typical measurements are electron/ion density, electron temperature, and energy distribution functions.

Fast Photography

The first session of the second week was entitled "Fast Photography" and was headed by Hugenschmidt, who is actively using optical techniques to study a variety of fast transient phenomena. The introductory address for this session was given by J.S. Courtney-Pratt (American Bell, Inc.) and was entitled "Research Trends in Fast Photography." Courtney-Pratt has been a pioneer in the field of high-speed photography, and in his lecture he described the variety, range, and precision of the many methods available for photographically recording fast phenomena.

The fast cameras are basically of two types: (1) those which record a faithful image of the event, usually with multiple frames, and (2) those which give a "streaked" record. The latter record the time evolution of some luminescent event such as a spark discharge or explosive detonations. The imaging cameras can be rotating drums, using conventional optics, or of the image conversion type, which use sophisticated photomultiplier schemes to produce images from very faint light sources. Courtney-Pratt pointed out that single-frame image cameras were capable of recording images in 3×10^{-14} seconds using suitable lasers for illumination. More typically, rotating drum cameras are capable of $\sim$50-ns resolution in framing modes and about 1 ns in streak modes. The use of image converter cameras has pushed these levels to about 1 ns for multiframe image systems and perhaps as low as 5×10^{-4} ns for streak records.

The following lectures in this session built upon the overview of Courtney-Pratt. "Recent Techniques of High-Speed Photography and Low-Level Image

Recording" by Pfeiffer, and "Electronic Ultra High-Speed Framing and Streak Cameras" by R.H. Price (Lawrence Livermore National Laboratory) provided details about the state of the art in imaging converter cameras and their application to specialized problems. Pfeiffer pointed out that the field of high-speed photography is currently dominated by streak or framing cameras which use image tubes with shutter or deflection electrodes. These systems are not suitable for applications where high dynamics, high resolution, and low distortion are required. Pfeiffer has used proximity focus image intensifiers with and without microchannel plates to produce high resolution and short exposure times (less than 1 ns). Price discussed the basic concepts of image converter devices, pointing out the ultimate limitations and tradeoffs to be made between exposure time, resolution, simplicity, and cost.

The session was closed with two lectures on applications of microchannel plates in nanosecond X-ray imaging by Chang and "Laser Photographic and Cinematographic Applications to the Investigation of Transient Phenomena" by Hugenschmidt. Table 4 summarizes the techniques discussed in this section.

Refractive Index Measurements

Optical diagnostics are used extensively to probe plasmas and flowing systems because, to a first approximation, they do not disturb the medium. The measurement of index of refraction and its derivative gives direct access to the electronic density, its gradients, and the hydrodynamics of the system under investigation. These measurements are usually made using ultra-short laser pulses or in conjunction with a streak camera if time resolution is a primary concern.

The basic techniques are pulsed laser interferometry, which measures the index of refraction; Schlieren photography, which measures the gradient in the index of refraction; and the shadowgram, which measures the second spatial derivative of the index of refraction. Holographic interferometry, while a more difficult technique, measures all the parameters mentioned above. This series of five lectures on various aspects of the optical technique was chaired by J. Stamper (Naval Research Laboratory). In an introductory lecture, "Concepts and Illustration of Optical Probing Diagnostics for Laser-Produced Plasmas," Stamper covered the fundamentals of the techniques, various interferometer arrangements, polarization effects, and the importance of adequate characterization of the laser beam used to probe the media under study.

Lectures by C. Popovics (Ecole Polytechnique), "Laser Interferometry, Streaked Photography, and Schlieren Imaging," and P. Forman (Los Alamos National Laboratories), "Noise Suppression and Sensitivity Modification in Index of Refraction Measurement," considered problems such as noise suppression and changes in sensitivity of these techniques as applied to specific problems. For example, Popovics used interferometry to measure the change in the density gradient produced by the probing laser, streaked shadowgraphy to measure velocity and acceleration of plates, and streaked Schlieren imaging to measure the time evolution of a density gradient in the plasma. These examples tend to illustrate the versatility of the technique and illustrate a few of the many applications for index measurements.

Holographic interferometry is a more powerful tool and, while more difficult experimentally, contains in the recorded phase information all the data obtained from the individual techniques described above. There were two lectures describing holographic technique. The first was by Chang, "Four Frame Holography and Thompson Scattering in a Pulse Power Environment." He illustrated application of the technique in the very demanding environment associated with large pulsed machines. The second lecture was by G. Busch (KMS Fusion, Inc.), "Twenty Picoseconds Pulsed UV Holographic Interferometry of Laser-Induced Plasmas: State of the Art." He discussed the state of the art in a

laboratory environment and clearly illustrated the excellent time resolution and spectral versatility of the technique. Table 5 summarizes the techniques used to measure index of refraction and its derivatives.

X-ray Diagnostics

As a diagnostic tool, X-ray optics have been in use since the late 1920s; however, problems associated with medicine, inertial confinement fusion, and weapons research have produced many advances in the state of the art, primarily in sources and X-ray optics. Optical elements such as X-ray mirrors, microscopes, telescopes, condenser lenses, filters, interferometers, and coded apertures are among the most important developments.

This section was chaired by N. Peacock (Culham Laboratory). The "shutter speed" for X-ray systems is governed by the X-ray pulse duration and the intensity of the pulse. Both are source/power problems. In his introductory lecture, Peacock described X-ray sources and their applications and characteristics. In his second and third lectures, Peacock discussed "X-ray Spectral Dispersion Techniques" and the state of the art in the search for X-ray lasers. He described efforts to produce X-ray lasers and the difficulty of obtaining sufficient "pump power" to produce population inversion.

Flash radiography has always been used and was primarily developed for photographing dense objects in a less-dense obscuring media. Some of the earliest uses were the exploration of detonation waves and detonation-produced shock waves in the presence of "smoke" and detonation products. The technique is still used for that purpose and was described by L. Jannet (Institut Franco-Allemand de Recherches de Saint-Louis) in a paper entitled "Flash X-Ray Radiography and X-Ray Diffraction Measurements of Shock Propagation." The most novel aspect of this paper was the use of flash X-ray beams to determine the change in the atomic lattice parameter under dynamic shock conditions. For shock waves with amplitudes greater than 100 kb, the density chance can be as high as 20 percent. On an atomic level, this results in a corresponding change in the lattice parameter which affects the diffraction angle as given by the Bragg equation. This technique was applied to the study of sodium chloride.

The many advances in the technology associated with X-ray diagnostics were described by R. Price (Lawrence Livermore National Laboratory) and R. Day (Los Alamos National Laboratories). Price's lectures were entitled "X-Ray Optics and Imaging Systems Using Reflecting Optics and Coded Apertures" and "X-Ray Streak Cameras and Array Detectors." These papers described advances in the state of the art which were motivated by the need to observe the collapse of pellets in inertial confinement fusion experiments. Price discussed the principles of grazing incidence reflection, geometries for X-ray optics, X-ray Fresnel lenses and zone plates, multilayer reflection coatings, and the use of these devices in the design and construction of X-ray microscopes and telescopes. These devices can resolve pellet compression on the micron scale and are associated with the laser-driven inertial confinement fusion program at the Lawrence Livermore National Laboratory.

Chang described similar developments and applications of X-ray microscopy at Sandia National Laboratories, where pellet implosion by particle beams is being studied. The particle beam fusion accelerators present interesting geometric constraints which necessitate unique custom designs in the X-ray system. In the Sandia machine, three X-ray sources, of a few nanoseconds duration, were used to obtain multiexposure photographs of the collapse event.

The last major lecturer in this section was Day. His lectures, entitled "Non-Dispersive Low Energy X-Ray Detectors and Their Characteristics, Absolute Energy and Spectral Dependence" and "Fiber Optic Technology X-Ray Transducers," tended to focus on the state of

the art in detector and imaging techniques. Although of general interest, these techniques are applicable specifically to telescopes and microscopes used to study pellet implosion. Table 6 summarizes the characteristics of X-ray diagnostics as presented in this section of the ASI.

Spectroscopy

Plasmas and plasma phenomena are an integral part of many of the applications of power technology. They are useful in switching, are used as a lasing medium, and are detrimental when they are formed as part of a catastrophic failure in electrical breakdown. Plasmas are difficult to probe with material devices without introducing serious distortion. A much more convenient technique is time-resolved spectroscopy of the emitting plasma. The technique can be applied over a wide range of optical wavelengths and can be optically active (laser-induced emission) or passive, using the natural plasma emissions. Excited atomic and ionized species provide a means of sensing electron, ion, and neutral atom temperatures and density functions. In addition, local values of electric and magnetic fields can be determined using Zeeman splitting and Thompson scattering. Spectroscopy in the time-resolved mode allows the spatial and temporal characteristics of the plasma to be determined.

The last 2 days of the ASI were devoted to these techniques. The first session was chaired by Professor H. Greim (University of Maryland). In his introductory lecture, Greim described the multiphoton processes, Coherent Anti-Stokes Raman Scattering, and basic principles of plasma spectroscopy, covering the theoretical basis for spectroscopic methods, radiative and collisional processes, and the effect of transients and spatial gradients on such measurements as density, temperature, and fields.

Price, in a lecture entitled "Time Resolved Spectroscopic Instrumentation and its Application to Plasma Diagnostics," described a spectroscopic technique applicable to the X-ray region of the spectrum. Due to the short wavelengths involved and the time resolution desired, unique experimental techniques were used to design and construct a spectrograph which could also energy-discriminate. The time resolution was accomplished by coupling the spectrometer to the X-ray streak camera system previously mentioned.

The final lecture--"Spectroscopy of Laser Produced Plasmas," presented by G. Tondello (Padova University)--illustrated the application of emission spectroscopy to the study of laser-induced breakdown plasmas. The primary measurements made were the temperature and density in the breakdown media. Table 7 summarizes the basic techniques of emission spectroscopy as a plasma diagnostic.

Active Optical Techniques

An obvious extension of the passive spectroscopic technique for studying plasmas is to use an active process to excite a transition via resonant absorption. This allows "discrete frequency" spectroscopy and can be tuned to resonantly excite a given species within the plasma. In this way, a topology map can be constructed which shows concentrations of a given species. This last session was chaired by S. Davis (Air Force Weapons Laboratory) and covered "Laser Induced Fluorescence and Thompson Scattering."

In his introductory lecture, Davis described laser-induced fluorescent procedures. He described the equipment needed to implement the technique, gave examples of experimental arrangements, and described several applications, such as radiative lifetime determination, quenching cross-section measurements, energy transfer studies, and flow visualization.

In an analogous way, lasers can be used in a two-photon excitation scheme to make similar measurements. This technique was described by W.K. Bischel (Stanford Research Institute). He

pointed out that the two-photon process could give higher optical gain and sensitivity, although the experimental technique is more complex. Table 8 describes the active optical techniques.

Coherent Anti-Stokes Raman Scattering

Coherent Anti-Stokes Raman Scattering (CARS) is a relatively new spectroscopy technique which has extended the range of Raman spectroscopy in physical sciences. The technique is based on multiwave mixing of electric fields in a suitable medium. The mixing is coherent and is related to the sum and differences of the individual frequencies used in the process. Usually, three laser beams are employed. The mixing frequency W_0 is related to the other laser beam frequencies--W_1, W_2, W_3--by the relation $W_0 = W_1 - W_2 + W_3$, where $W_1 > W_2$. When $W_1 - W_2$ is associated with a Raman transition, nonlinear mixing is greatly enhanced. These Raman resonances constitute a CARS spectrum which can be scanned by varying W_1, or W_2, or both, and detected by the coherently generated signal at $W_0 = W_3 + W_R$.

J.J. Valentine (Los Alamos National Laboratories), in a paper entitled "Coherent Anti-Stokes Raman Scattering Techniques," described the basic theory and practical methods for applying the technique to the study of fast combustion processes, plasma diagnostics, time resolved spectroscopy in the biological sciences, and other areas--such as molecular beams. He described selection rules which govern the mixing, factors which determine the sensitivity, spectral line shape, and special techniques for reducing noise and undesirable background effects.

Finally, Peacock described the fundamentals of diagnostics based on Thompson scattering. Briefly, monochromatic electromagnetic radiation is scattered from free electrons in the system being diagnosed. In the scattering process, the laser photons are Doppler shifted in proportion to the velocities of the scattering electrons, resulting in scattered photons with the same distribution in wavelength space as the electrons' distribution in velocity space. By collecting the scattered light, one can use the wavelength distribution function to calculate T_e, the electron temperature, from the Doppler-broadened width of the spectrum; N_e, the electron density, from the wavelength-integrated amplitude of the spectrum; and the fluid drift velocity, V_d, from the entire shift of the spectrum away from the wavelength of the incident laser radiation.

Several factors influence these measurements. The environment is usually harsh, consisting of X-rays and radio-frequency noise, which can drastically influence the response of the associated electronic systems. Thompson scattering is very powerful and is often used to diagnose intense electron relativistic beams.

Table 1

Electro-Optical and Magneto-Optical Measurements

Diagnostic	Characteristic Time	Applicability Range	Cost	Versatility	Comments
Kerr Effect					• Trade-off between time response and sensitivity
$\bar{E}$	<1 ns	10 kV/cm–100 kV/cm	Moderate	Excellent	• Can extrapolate over a wide range • Δn quadratic in $\bar{E}$
V	<1 ns	5 kV–10 MV	Moderate	Excellent	• Provides electrical isolation • Limited to reasonably birefringent liquids • Solutions are usually good solvents • Uncertainty less than 1% but recording technique may be 5% or greater • Somewhat sensitive to field geography
Pockels Effect					• Solid media rather than liquid • Intrusive but electrically isolated
$\bar{E}$	0.001–0.1 ns	1 mV/cm–100 kV/cm	Expensive	Excellent	• Δn linear in $\bar{E}$
V	0.001–0.1 ns	50 V–1 MV	Expensive	Excellent	• Materials generally piezoelectric and sensitive to shock • Two linear regions of sensitivity • Long devices are sensitive but slow due to transient times • Fastest devices are special installations • Uncertainty in measurement dominated by recording system
Faraday Effect					• Linear effect • Electrical isolation
$\bar{H},\bar{B}$	0.1 ns	1 G–5 MG	Expensive	Excellent	• Small T dependence for diamagnetic materials, larger for paramagnetic
I	0.1 ns	50 A–10 MA	Expensive	Excellent	• Trade-off between time resolution and sensitivity • Sensitive to shock

Table 2

Conventional Measurement Techniques for Voltage and Current

Diagnostic	Characteristic Time	Applicability Range	Cost	Versatility	Comments
Voltage					
Resistive dividers	∿100 ps ∿1 ns ∿10 ns	<50 kV <500 kV >500 kV	Cheap Cheap Cheap	Limited Excellent Excellent	• 100-ps measurement requires TEM00 mode and considerable experimental techniques • Connections to system ground • Rise time geometry dependent • Intrusive • Usually requires secondary divider • Calibration not always at test conditions • Uncertainty on order of 5%
Capacitive dividers	∿1 ns ∿50 ps	>1 MV >100 kV	Cheap Moderate	Excellent Limited	• Intrusive measurement • Usually custom made • Calibration difficult • Low frequency cutoff ∿ RC
Current					
CVR/shunt	50 ps >500 ps 10 ns	10 kA 50 kA 1 MA	Moderate Moderate Moderate	Good Good Good	• Energy limited • Thermal sensitive • DC coupled • Noise source • Skin depth factors
Rogowski coil	0.5-1 ns	1 A-5 MA	Cheap	Excellent	• Leaks in strong B field • Intrusive • Requires integrator • Difficult to obtain current standard for calibration • Position independent • Uncertainty on order of 5%
Current transformers	10 ns	1 A-5 MA	Moderate	Excellent	• Does not require integrator • Volt-sec core limit • Intrusive • Uncertainty on order of 5%
Stripline coil di/dt	10 ps	$< 10^{12}$ A/s	Moderate	Medium	• Intrusive • Can average azimuthal nonuniformities • Uncertainty on order of 5%

Table 3

Miscellaneous Measurement Techniques

Diagnostic	Characteristic Time	Applicability Range	Cost	Versatility	Comments
Fields					
D-Dot probe	~100 ps	Limited to modest fields 50-100 kV/cm	Expensive	Moderate	• Rise time related to sensor size • Free field measurement • Geometry sensitive • TEM00 mode for fast rise • Uncertainty 10% or greater • Requires primary standard
B-Dot sensor	<1 ns		Cheap	Medium	• Speed related to size • Position dependent/calibrate in place • Can average azimuthal nonuniformities • Requires primary standard
Current					
θ probe	<1 ns	1-10 kA	Cheap	Medium	• Low frequency cutoff ~ L/R
Faraday cup	5 ns	0.1-2.5 kA/cm	Moderate	Limited	• Susceptible to background plasma • Calibration is a function of current density • Requires experimental finesse

Table 4

Summary of Optical Techniques for Measuring Geometry/Velocity

Diagnostic	Characteristic Time	Applicability Range	Cost	Versatility	Comments
Imaging Cameras					• Calibrated using standard resolution chart • Extremely short time resolution demands trade-off with compexity and accuracy • Velocity measurement requires metric in image • Multiframe system complex • May require intense light source • 1.6-ns frame rate commercially available • Used to measure changes in surface topology
Single frame	3×10^{-5} ns	Extensive	Expensive	Excellent	
Rotating mirror (multiframe)	50 ns	Extensive	Expensive	Excellent	
Image converter (multiframe)	<1 ns	Extensive	Expensive	Excellent	
Speckle	<1 ns	Limited	Modest	Limited	
Streak Cameras					
Single mirror	1 ns	Extensive	Expensive	Excellent	• Optically passive
Multimirror	0.1 ns	Extensive	Expensive	Limited	• Need intense light source
Image converter	5×10^{-4} ns	Extensive	Expensive	Excellent	• Can be used to measure relative optical intensity • Interpretation sometimes difficult

Table 5

Refractive Index Measurements

Diagnostic	Characteristic Time	Applicability Range	Cost	Versatility	Comments
Index of refraction, N					• Nonperturbing • Accuracy depends upon symmetry • Uncertainty ~10%
Pulsed laser interferometer	<0.1 ns	Can be employed over a wide range of parameters	Moderate	Excellent	• Interpretation sometimes difficult • Sensitivity limits
Gradient N Schlieren	<0.1 ns	Can be employed over a wide range of parameters	Moderate	Moderate	• Nonperturbing • Qualitative • Low accuracy in measurment • "Streaked" to obtain velocity • Interpretation • Sensitivity limits
Second derivative of N Shadowgram	<0.1 ns		Moderate	Moderate	• Nonperturbing • Difficult to obtain quantitative results • Interpretation • Sensitivity limits
N, dN/dx d^2N/dx^2 holographic interferometry	<0.1 ns	Can be employed over a wide range of parameters	Moderate	Excellent	• Nonperturbing • Multiphenomena recorded on a single plate • Highly stable and after the fast focusing • Interpretation sometimes difficult

Table 6

X-ray Techniques for Fast Diagnostics

Diagnostic	Characteristic Time	Applicability Range	Cost	Versatility	Comments
Flash X-ray: all imaging techniques--telescopes/ microscopes	2 ns	Limited	Expensive	Limited	• Basic technique is simple. Experimental arrangment/application may lead to complex custom designs • Usually used to measure "shape" or "velocity" in an obscuring media • Limited to a few frames • Frame rate and number pulser dependent • Frame rated up to 10^9/s • Must use 1 pulser/frame at high rates
X-ray streak	0.02 ns	Limited	Expensive	Limited	• Custom design • Used as a diagnostic in fusion pellet compression experiments

Table 7

Emission Spectroscopy Diagnostics

Diagnostic	Characteristic Time	Applicability Range	Cost	Versatility	Comments
State Ident.					
Optical region	<1 ns	>1 part in 10^{12}/cc	Inexpensive	Excellent	• Flexible • Standard technique • Large uncertainty in measurements
X-ray region	15 ps	1 part in 10^4	Expensive	---	• Large uncertainty in measurements • Flexible technique • Custom designs
Ion/Neutral Density					
Optical region	10 ns	10^{12}-10^{18}/cc	Inexpensive	Good	• Must understand theoretical basis for multicomponent system for analysis • Large uncertainty
X-ray region	15 ps	10^{15}-10^{23}/cc	Moderate	Excellent	• Total population inferred from excited population • Needs good spectral resolution
Ion/Neutral Temperature					
Optical region	10 ns	0.2-10 eV	Inexpensive	Limited	• Complicated by line broadening by competing processes • Uncertainty on order of 20%
X-ray region	15 ps	100 eV-1 keV	Moderate	Limited	• Line broadening by competing processes • Uncertainty greater than 20%
Elect. Energy Dist. Fcn.					
X-ray region	15 ps	~10^{18}	Moderate	Limited	• Complicated analysis • Inaccurate • Needs automatic data processing
Elect. Temperature					
Optical region	1 ns	0.1-100 eV	Inexpensive	Good	• Complicated analysis • Needs automatic data processing techniques
X-ray region	15 ps	100 eV-100 keV	Moderate	Good	• Uncertainty no greater than 10% • Sophisticated technique
Species Ident.					
Optical region	1 ns	1 part in 10^4	Moderate	Limited	• Cannot detect ground state • Requires bright source • Time frame plasma dependent • Related to radiative lifetimes
X-ray region	15 ps	1 part in 10^4	Expensive	Limited	• Limited to bright sources • Time/brightness trade-off • Limited life streak camera • Difficult below 1 keV

Table 8

Summary of Active Optical Techniques

Diagnostic	Characteristic Time	Applicability Range	Cost	Versatility	Comments
Ion/Neutral Density Laser-induced fluorescence (LIF)	~1 ps	10^{10}-10^{19}/cc	Expensive	Good	• Requires good experimental technology • Signal averaging • Complex • Large uncertainty in measurements
Coherent Anti-Stokes Raman Scattering (CARS)	~1 ps				
Elect. Temperature Thompson Scattering	~1 ns	1-5 keV	Moderate	Excellent	• Useful in harsh environment • Versatile technique • Adaptable to many geometries • Nonintrusive
Species Ident. LIF	1 ps	10^{10}-10^{14}/cc	Expensive	Excellent	• Signal averaging needed • Nonintrusive • Difficult experimentally • Laser limited
CARS	1 ps	$>10^{12}$/cc 100 ppm	Moderate	Excellent	• Excellent for time dependence environment • Excellent in hostile environment • Useful for a wide range of transients • Laser limited
Multiphoton	1 ps	Only for weakly ionized, low n_e, T_e (1 part in 10^9)	Expensive	Moderate	• Neutral detection 1 part in 10^9 • Absolute accuracy difficult • All atoms and molecules • Laser limited
State Ident. CARS	1 ps	$>10^{12}$/cc>100 ppm	Moderate to expensive	Excellent	• Good spatial resolution • All species • Unsensitive to stray fields • Atomic or molecular • Laser limited
LIF	1 ps	$>10^{10}$/cc>100 ppm	Expensive	Moderate	• Limited by proper laser choice • Atomic or molecular
Multiphoton	1 ps		Expensive	Moderate to good	• Single state sensitive • All species • Neutrals
Fields (LIF) dE/dT	1 ns	E>1 keV/cm	Moderate	Poor	• Large uncertainty • Difficult experimentally • Sensitive to $\bar{E}$ not $\dot{E}$
$\bar{B}$ Zeeman splitting	1 ns	---	Cheap	Poor	• Analysis difficult
Ion/Neutral Temperature LIF	ps	---	Expensive	Moderate	
Elect. Energy Dist. Fcn. Thompson scattering	ns	$>10^{13}$	Expensive	Limited	• Difficult measurement • Automatic data processing helpful • Small σ
Elect. Density Thompson scattering	ps - ns	10^{12}-10^{19}/cc	Expensive	Limited	• Trouble in weakly ionized plasmas • Small σ • Resolution related to laser power • Laser limited

APPENDIX: ASI PARTICIPANTS

Jean Jacques Aliff
Swiss Federal Institute of Technology
High Voltage Laboratory
Physikstrasse 3
8092 Zurich
Switzerland

Dr. G. Baldo
Padova University
6/A Gradenigo
35100 Padova
Italy

Dr. Walter Bauer
Kernforschungszentrum
Karlsruhe, 1K
Postfach 3640
D-7500 Karlsruhe
Federal Republic of Germany

Dr. Carl Baum
NTATT
Kirtland AFB, NM 87117

Dr. David M. Benenson
State University of New York-Buffalo
Dept. of Electrical and Computer Engr.
4232 Ridge Lea Road
Amherst, NY 14226

Arnaldo Bertazzi
CESI
Via Rubattino, 54
20134 Milano
Italy

Hubert Biero
CEA
Centre de Vaujours
BP7
93270 Sevran
France

Dr. William K. Bischel
Stanford Research Institute
Molecular Physics Laboratory
MS-PN-027
333 Ravenswood Avenue
Menlo Park, CA 94025

Dr. Laird P. Bradley
Lawrence Livermore National Lab., L-490
P.O. Box 5508
Livermore, CA 94550

Dr. Alexander Brandelik
Kernforschungszentrum Gmbh
Postfach 3640
D-7500 Karlsruhe
Federal Republic of Germany

Garland E. Busch
KMS Fusion, Inc.
P.O. Box 1567
Ann Arbor, MI 48106

Noel Camarcat
Commissariat a l'Energie Atomique
Centre d'Etudes de Valduc
B.P. 14-21/IS SUR TILLE
France

Dr. Christos Capellos
Energetic Materials Division
LCWSL, AARADCOM, EMD
Bldg. 3022, DRDAR-LCE-D
Dover, NJ 07801

George Chandler
Los Alamos National Laboratory
MS-F639
P.O. Box 1663
Los Alamos, NM 87545

Dr. Jim Chang
Sandia National Laboratories
Diagnostics Division 1234
Albuquerque, NM 87185

Dr. Paul Chatterton
University of Liverpool
Department of Electrical Engineering and
Electronics
Liverpool L69 3BX
United Kingdom

Dr. Jerome R. Clifford
Advanced Technology Division
Air Force Weapons Laboratory
AFWL/NTY
Kirtland AFB, NM 87117

Dr. Chathan M. Cooke
Massachusetts Institute of Technology
High Voltage Research Laboratory
155 Massachusetts Avenue
Cambridge, MA 02139

Dr. Jeofry Stuart Courtney-Pratt
American Bell, Inc.
Crawfords Corner Road
Nolmdel, NJ 07733

Dr. Steve Davis
AFWL/ARAP
Kirtland AFB, NM 87117

Dr. Robert H. Day
Los Alamos National Laboratory
MS-D410
P.O. Box 1663
Los Alamos, NM 87545

David L. Demske
Detonation Physics Branch
Energetic Materials Division
Naval Surface Weapons Center/White Oak
Silver Spring, MD 20910

Dr. Marco DiCapua
Physics International
2700 Merced Street
San Leandro, CA 94577

Dr. D.A. Eastham
Daresbury Laboratory
Daresbury, NR
Warrington WA4 4AD
Cheshire
United Kingdom

Mario Favre
Imperial College
Physics Department
London SW7 2BZ
United Kingdom

Dr. David B. Fenneman
Code F12
Naval Surface Weapons Center
Dahlgren, VA 22448

Dr. Ralph Fiorito
Code R41
Naval Surface Weapons Center/White Oak
Silver Spring, MD 20910

C. Flatau
Tektronix Europe B.V.
P.O. Box 8272280AV
Amstelveen
The Netherlands

Dr. Peter R. Forman
CTR-8, MS-F369
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545

Dr. Rudolf Germer
Technical University of Berlin
Zieten Str. 2
D. Berlin 30
Federal Republic of Germany

Dr. Werner Graf
SRI International
Location 40477
333 Ravenswood Avenue
Menlo Park, CA 94025

Dr. Hans Griem
Department of Physics
University of Maryland
College Park, MD 20742

Dr. Ronald J. Gripshover
Code F12
Naval Surface Weapons Center
Dahlgren, VA 22448

Dr. A.H. Guenther
Chief Scientist
Air Force Weapons Laboratory/CA
Kirtland AFB, NM 87117

Dr. Martin A. Gundersen
Department of Electrical Engineering
University of Southern California
SSC 420, MC-0484
University Park
Los Angeles, CA 90089

Norman E. Hansen
Lawrence Livermore National Laboratory
MS L-45
P.O. Box 808
Livermore, CA 94550

Dr. Robert Hebner
Building 220, Room B-344
National Bureau of Standards
Washington, DC 20234

Dr. Lother Hoeft
BDM Corporation
1801 Randolf Road, SE
Albuquerque, NM 87131

Walter Wayne Hofer
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550

Dr. M. Hugenschmidt
Deutsch-Franzosisches Forchungsinstitut
12, rue de l'Industrie
68003 Saint Louis
Haut-Rhin
France

Dr. Stanley Humphries, Jr.
Dept. of Chemical and Nuclear Engr.
Farris Engineering Center
University of New Mexico
Albuquerque, NM 87131

Dr. Anthony K. Hyder, Jr.
Auburn University
202 Samford Hall
Auburn, AL 36849

F. Jamet
Institute Franco-Allemand de Recherches
de Saint-Louis
Boite Postale No. 301
68301 St. Louis, Cedex
France

Dr. C.A. Kapetanakos
Code 4704
Naval Research Laboratory
Department of the Navy
Washington, DC 20375

Dr. Helmut A. Koehler
Lawrence Livermore National Lab., L-43
University of California
P.O. Box 808
Livermore, CA 94550

Dr. Peter Krehl
Ernst Mach Institut
Fraunhofer Iustitut fur Kurzzeitdynamik
Eckerstasse 4
D-7800 Freiburg
Federal Republic of Germany

Dr. M. Kristiansen
Department of Electrical Engineering
Texas Tech University
Lubbock, TX 79409

Dr. Herman G. Krompholz
Department of Electrical Engineering
Texas Tech University
P.O. Box 4439
Lubbock, TX 79409

Dr. Erich E. Kunhardt
Ionized Gas Laboratory
Department of Electrical Engineering
Texas Tech University
Lubbock, TX 79409

Gerd F. Kuscher
Ernst Mach Institute of the Fraunhofer Company
Eckerstr. 4
7800 Freiburg
Federal Republic of Germany

Dr. Javaid R. Laghari
Dept. of Electrical and Computer Engr.
State University of New York-Buffalo
4232 Ridge Lea Road
Amherst, NY 14226

Ramon Leeper
Diagnostics Division 1234
Sandia National Laboratories
Albuquerque, NM 87185

Lawrence H. Luessen
Head, Directed Energy Branch (F12)
Naval Surface Weapons Center
Dahlgren, VA 22448

Dr. Michael Mentzoni
University of Oslo
Institute of Physics
Box 1038
Blindern Oslo 3
Norway

Dr. Howard Thomas Miles
Department of Physics
University College of Swansea
Singleton Park
Swansea, SA2 8PP
United Kingdom

Dr. G. Marshall Molen
Department of Electrical Engineering
Old Dominion University
Norfolk, VA 23508

Gerard Mourou
University of Rochester
Laboratory for Laser Energetics
250 East River Road
Rochester, NY 14623

Dr. Norris S. Nahman
Fields Characterization Group, 723.03
EM Fields Division
National Bureau of Standards
325 Broadway
Boulder, CO 80303

Andre Nicholas
Commissariat a l'Energie, Atomique
B.P. 14
21120 IS SUR TILLE
France

Dr. Lutz Niemeyer
Brown Boveri Research Center
CH 5405 Baden
Switzerland

Dr. Eugene E. Nolting
Naval Surface Weapons Center/White Oak
Silver Spring, MD 20910

Aron Nudelman
Princeton Plasma Physics Laboratory
P.O. Box 451, Building 1-N
Princeton, NJ 08544

Dr. Nicol J. Peacock
Culham Laboratory
Division B UKAEA
Abingdon, Oxfordshire OS14 3DB
United Kingdom

R.A.G. Perryman
The Welding Institute
Abington Hall
Abington, Cambridge CB1 6AL
United Kingdom

Dr. W. Pfeiffer
Fachgebiet Elektrische
Mesztechnik, Fachbereich 17
Technische Hochschule Darmstadt
Scholszgraben 1
6100 Darmstadt
Federal Republic of Germany

Mrs. Claude Popovics
Laboratoire de Physique des Milieux
Ionises
Ecole Polytechnique
91128 Palaiseau Cedex
France

Dr. Robert H. Price
Lawrence Livermore National Lab., L-473
P.O. Box 5508
Livermore, CA 94550

Dr. Joseph M. Proud
GTE Laboratories
40 Sylvan Road
Waltham, MA 02254

Dr. Henry L. Pugh, Jr.
Air Force Office for Scientific Research
Building 410
Bolling AFB, DC 20332

Dr. A. Haq Quershi
Electrical and Computer Engineering
Wayne State University
Detroit, MI 48202

Dr. Michael Raleigh
Code 4763
Naval Research Laboratory
Washington, DC 20375

Guiseppe Rizzi
CESI
Via Rubattino, 54
20134 - Milano
Italy

Dr. Frank Rose
Science Advisor
Code F04
Naval Surface Weapons Center
Dahlgren, VA 22448

Dr. Wijnand R. Rutgers
N.V. KEMA
P.O. Box 9035
6800 ET Arnhem
The Netherlands

Dr. Karl H. Schoenbach
Department of Electrical Engineering
Texas Tech University
P.O. Box 4439
Lubbock, TX 79409

Dr. Klaus Schon
Physikalisch Technishe Bundesanstalt
Bundesalle 100
D-3300 Braunschweig
Federal Republic of Germany

Dr. Adolf J. Schwab
High Voltage Research Laboratory
University of Karlsruhe
Karlsruhe
Federal Republic of Germany

Daniel L. Schweickart
Air Force Wright Aeronautical Labs
Aero Propulsion Laboratory
AFWAL/POOS-2/Building 450
Wright-Patterson AFB
Dayton, OH 45433

Dr. Fred Schwirzke
Department of Physics
Naval Postgraduate School
Monterey, CA 93940

Dr. Robert Seeboeck
CERN, European Organization for Nuclear Research
PS Division
CH-1211 Geneva 23
Switzerland

Dr. John D. Sethian
Code 4762
Naval Research Laboratory
Washington, DC 20375

Dr. Timothy L. Ksvarenina
AFIT/ENG
Air Force Institute of Technology
Wright-Patterson AFB
Dayton, OH 45433

Dr. John Stamper
Code 4771
Naval Research Laboratory
Washington, DC 20375

S. Streiff
Nicolet Oscilloscope Division
5225 Verona Road
P.O. Box 4288
Madison, WI 53711

Dr. Tangali S. Sudarshan
Electrical and Computer Engineering
University of South Carolina
Columbia, SC 29208

Dr. Timm H. Teich
FG Hochspannung
Federal Institute of Technology
ETHZ
Physikstrasse
3 CH 8092 Zurich
Switzerland

Dr. James E. Thompson
Electrical Engineering Department
University of Texas - Arlington
Arlington, TX 76019

Dr. G. Tondello
Padova University
6/A Gradenigo
3S100 Padova
Italy

Dr. David Tuma
Electrical Engineering Department
Carnegie-Mellon University
Schenley Park
Pittsburgh, PA 15213

Dr. James J. Valentini
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545

Dr. Ihor Vitkovitsky
Head, Plasma Technology Branch
Code 6670
Naval Research Laboratory
Washington, DC 20375

E.B. Vossenberg
CERN, European Organization for Nuclear Research
CH-1211, Geneva 23
Switzerland

F. Thomas Warren, Jr.
831 Statler Road
Columbia, SC 29210

Dr. D. John Wiesinger
Hochschule der Bundeswehr, Munchen
ET/WE 7 El Engergieversorgung
D-8014 Neubiberg
Federal Republic of Germany

Dr. Frazer Williams
Department of Electrical Engineering
Texas Tech University
Lubbock, TX 79409

Dr. G.G. Wolzak
Eindhoven University of Technology
P.O. Box 513
5600 MB Eindhoven
The Netherlands

Dr. Markus Zahn
High Voltage Research Laboratory
Building N-10
Dept. of Electrical Engineering and
Computer Science
Massachusetts Institute of Technology
Cambridge, MA 02139

Jeffrey W. Warren
9505 Puritan Road
Columbia, SC 29209

Dr. R. Seebock
Siemens AG Erlaugeu
ZFE TPH 3
Gunther-Scharowsky - Str.
D-8520 Erlangen
Federal Republic of Germany

Professor Dr. F. Christiauseu
Physikalisches Institut der Universitaf
Taudeurlabor
Erwin-Rommel Str. 1
D-8520 Erlangen
Federal Republic of Germany

Dr. J.A. Stamper
Code 4732
Naval Research Laboratory
Washington, DC 20375

Dr. Roger Dougal
Electrical and Computer Engineering
University of South Carolina
Columbia, SC 29208

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